Ultrasonic/Sonic Driller/Corer (USDC) as a Subsurface Sampler and Lab-on-a-Drill for Planetary Exploration Applications

Y. Bar-Cohen, S. Sherrit, X. Bao, M. Badescu, J. Aldrich and Z. Chang
Jet Propulsion Laboratory (JPL)/Caltech, Pasadena, California, USA

Abstract: The search for existing or past life in the Universe is one of the most important objectives of NASA's mission requiring effective sampling tools. In support of this objective, a series of novel mechanisms that are driven by an Ultrasonic/Sonic actuator have been developed to probe and sample rocks, ice and soil. This mechanism is driven by an ultrasonic piezoelectric actuator that impacts a bit at sonic frequencies through the use of an intermediate free-mass. Ultrasonic/Sonic Driller/Corer (USDC) devices were made that can produce both core and powdered cuttings, operate as a sounder to emit elastic waves and serve as a platform for sensors. For planetary exploration, this mechanism has the important advantage of requiring low axial force, virtually no torque, and can be duty cycled for operation at low average power. The advantage of requiring low axial load allows overcoming a major limitation of planetary sampling in low gravity environments or when operating from lightweight robots and rovers. The development of the USDC is being pursued on various fronts ranging from analytical modeling to field testing while implementing mechanisms improvements for a wide range of potential applications. While developing the analytical capability to predict and optimize its performance, efforts are made to enhance its capability to drill at higher power and high speed. Taking advantage of the fact that the bit does not require rotation, sensors (e.g., thermocouple and fiberoptics) were integrated into the bit to examine the borehole during drilling. Since the USDC is driven by piezoelectric actuation mechanism it can be designed to operate at extreme temperature environments from very cold as on Titan and Europa to very hot as on Venus. In this paper, a review of the latest developments and applications of the USDC is given.

I. Introduction

In-situ acquisition and analysis of samples from various planets in the solar system is increasingly an objective of the NASA exploration missions and effective mechanisms are being sought to meet this need. Rotary drilling techniques are limited by the need for high torques and force on the bit, bit wear, high power consumption and an inability to efficiently duty cycle. To address these limitations, the JPL's Advanced Technologies Group and engineers from Cybersonics, Inc. jointly developed the Ultrasonic/Sonic Driller/Corer (USDC) [1-2; http://ndeaa.jpl.nasa.gov/nasa-nde/usdc/usdc.htm]. Following the development of this novel mechanism (see Fig. 1) the team conceived many innovative designs that were disclosed in NASA New Technology Reports and patents [e.g., 3-17]. The USDC requires low axial force, thereby overcoming one of the major limitations of planetary sampling using conventional drills in low gravity environments. This capability offers the advantage of being able to perform tough tasks of drilling and coring in hard rocks, ice and packed soil using relatively small force and relatively lightweight hardware. The USDC was demonstrated to: 1) drill ice and various rocks including granite, diorite, basalt and limestone, 2) not require bit sharpening, 3) operate at low and high temperatures, and 4) operate at low average power using duty cycling. A series of modifications of the USDC basic configuration were made resulting in the development of the Ultrasonic/sonic Rock Abrasion Tool (URAT), Ultrasonic/Sonic Gopher for deep ice drilling, the Lab-on-a-drill, and many others.

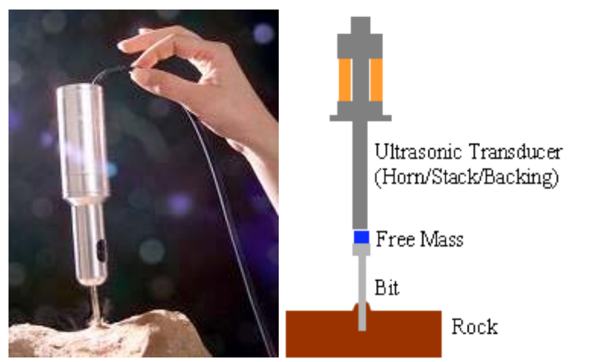

FIG. 1: A photographic view of the USDC showing its ability to core with minimum axial force (left), and a schematic cross-section view (right).

The USDC consists of three key components: actuator, free-mass and bit (see Fig. 1) [2]. The actuator operates as a hammering mechanism that hits the free-mass and in turn the bit is hit to fracture the rock that is in contact with the bit. The actuator consists of a piezoelectric stack with backing for forward power delivery and a horn for amplification of the induced displacement. The USDC is actuated by a piezoelectric stack that is driven in resonance and is held in compression by a stress bolt that prevents its fracture during operation. In the basic design the piezoelectric stack has a resonance frequency of about 20-kHz. Unlike typical ultrasonic drills where the bit is acoustically coupled to the horn, in the USDC the actuator drives a free flying mass (free-mass), which bounces between the horn tip and the drilling/coring bit converting the ultrasonic impacts to hammering at sonic frequencies. The impacts of the free-mass create stress pulses that propagate to the interface of the bit and the rock onto which the USDC is placed in contact. The

* E-mail: yosi@jpl.nasa.gov, Web: http://ndeaa.jpl.nasa.gov

rock is fractured when its ultimate strain is exceeded at the rock/bit interface.

II. Analytical modeling the operation of the USDC

The drilling mechanism of the USDC involves rock fracture via impact loading (percussion). To better understand the fracture of rocks under impact loading, a finite element model using ANSYS (a finite element software package) was developed to investigate the propagation of the induced stress. Results were derived by assuming that the rock medium is made of isotropic material with various values of Young's modulus and Poisson's ratio of 0.3. Contour maps of the maximum principal strain were plotted and used to indicate the areas where the rock is fractured and to determine how the elastic waves propagate in the rock prior to fracture. This analytical capability allows for an estimate of the limitations on the diameter of the cored material that maintains structural integrity. Using this analysis, it is estimated that the minimum diameter of intact cores that can be produced is about 4-5 mm for medium to hard materials. The drilling rates in various rocks at 10-W average power were calculated and a graph is shown in Fig. 2 for various rock stiffness values. This capability to predict the performance of the drill allows optimizing the design of effective USDC units.

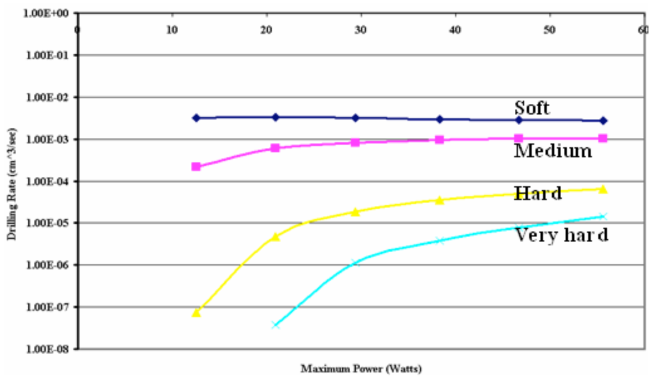

FIG. 2: Analytical drilling rates in rocks with various hardness levels using 10W average power. The rocks are classified by their compression strength, where: Soft: 0 – 50; Medium: 50 – 100; Hard: 100 – 200; and Very hard: >200 (MPa).

V. USDC with various novel horns

The horn is an important part of the USDC actuator amplifying the produced vibration amplitude. Generally, the horn is made as a step from the diameter of the piezoelectric stack elements to the tip diameter with the amplification increasing as the ratio of the square of the diameters (area ratio). In many cases, there are specific requirements for the configuration of the horn. For the reported studies the authors developed novel designs and examples include small length and volume as for the Ultrasonic rock abrasion tool or a generator of large impact forces as is the case of the ultrasonic Gopher.

Folded horn

The length of the horn in the USDC actuator can be a concern when there are volume constrains and reduction of its size can be critical to the integration of the unit as a sampler. A compact shape horn was developed with hollow configuration that amplifies vibrations of high power actuation mechanisms. This folded horn can be configured in axis-symmetric and planar shapes to provide manufacturing options. The use of reflectors at the folds allows for control of the phase of the reflected strain wave and for the introduction of constructive bending vibrations that enhance the amplification of the actuation.

Dog-bone shape horn

Recently, a dog-bone design was introduced and demonstrated to improve the drilling performance. This horn design brings to the system the benefits of allowing bit mounting to the actuator and of operating with dual free-mass to permit both forward and reverse hammering. For this purpose, various horn designs were examined analytically and compared to conventional and solid shape horns and analytically it was shown that the dog-bone design has a superior performance. To demonstrate the capability of the dog bone horn a finite element modeling was used to determine the control parameters and showed the excitation of superior tip displacement and velocity. A view of the U/S gopher using the dog bone horn is shown in Fig. 3 (right side of the item on the top).

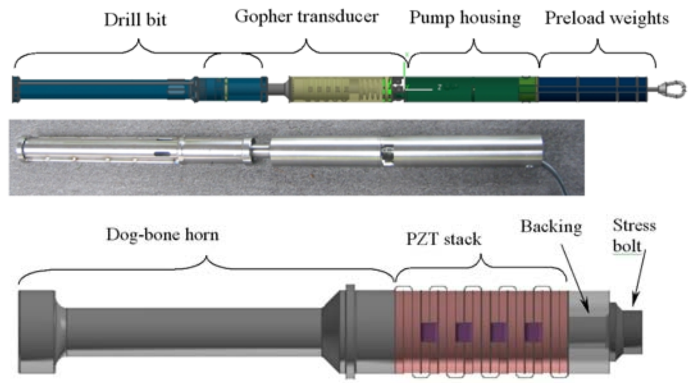

FIG. 3: A view of the new USG with a dog bone horn.

VI. USDC with various bits

Ultrasonic/Sonic Rock Abrasion Tool (URAT)

Abrasion of the surface of a rock using low axial force and limited average power is needed to remove weathered layers from rock surfaces and expose pristine sections. Conventional rotating mechanisms require high axial loads and they are involved with contamination sources such as lubricants and ground filings from their motor gearbox. The use of the USDC offers significant advantages in requiring low axial force, low average power, low number of components, and the capability to produce a mechanism of removal of powered cuttings from the borehole. In its original configuration, the USDC was designed to drill or core and it was not designed to remove layers of weathered material from rocks. To address the need for an abrasion tool an Ultrasonic Rock Abrasion Tool (URAT) was developed. For this purpose, an abrasion bit was designed similar to the hammering surface of a meat tenderizer. Teeth were machined onto the bottom of the disk that is part of the abrasion bit. These teeth amplify the drilling pressure and enhance the action of the URAT. A schematic cross-section drawing is shown in Fig. 4 illustrating the components and the compact structure of the URAT. A view of abraded basalt is shown in Fig. 5. The abrasion tool consists of a 1.6 in. (40-mm) diameter disk that is attached to a shank that fits around the horn. The free-mass is placed inside the shank between the horn and the bottom of hole along the inner part of the bit. On the bottom of the disk teeth were machined in the form of pins that stick out of the disk.

Interchangeable bit

One of the most promising benefits of the USDC is the simple interface it provides to the bit, and the simplicity of the shape of the bit itself. The use of multiple bits will be essential in future missions as it is simply not practical to fly a multitude of samplers to support various instruments. These tasks can, however, be accomplished using a single actuator that utilizes multiple bits for drilling, coring, surface preparation, and sampling, where the bits can be exchanged as needed. The bit does not require sharpening, but, if a bit where to get damaged for whatever reason, it could simply be replaced.

All in one bit

The use of multiple bits requires a manipulation system to exchange bits as needed. If a manipulation system is not available it is highly desirable to accomplish as many functions as possible using a single bit. For this purpose, an all-in-one bit was developed and demonstrated. The bit consists of a tube with a wedge at the top of the inner surface of the bit, a set of springs near the tip and a push rod that is inserted thru a center hole in the bit. Once a core is produced at a length of the inner section of the bit, the wedge introduces transverse forces at the top of the core to cause maximum stress near the root and shear fracture. The side springs hold the produced core for removing from the borehole. The core is extracted when needed from the bit using the push rod from the top of the bit.

Powdered cuttings sampler

In prior development of powder cuttings samplers, the authors have shown that the USDC offers significant advantages in requiring low axial force, low average power, low number of components, and capability to produce powered samples directly from rock [14-15]. However, the previous designs required using rock fragments that are inserted into the crushing section of the device [12] or required pressurized gas to transport the powder from the sampled rock [14]. In a recent modification, the authors used trapping cavities that acquire the upward traveling powder that enter a hollow inner section of the bit (see Fig. 6) and retain the particles until they need to be collected or disposed of.

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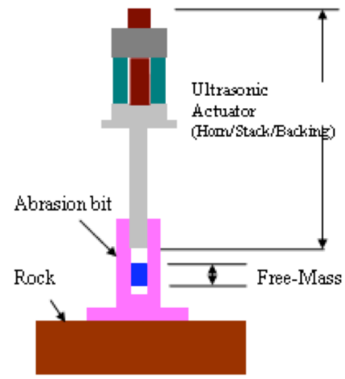

FIG. 4: Schematics of the Ultrasonic Rock Abrasion Tool (URAT)

FIG. 5: Photographic view of basalt that was abraded by the URAT. The footprint of the abrasion bit can be seen on the surface.

Using design models that the authors developed for the planar folded horn configuration [17] a compact sampler weighing 265-g was produced. A hollow bit was made with an end-effector section that is brazed on the bit and has teeth to enhance the cutting performance. The bottom of the bit was made with holes that allow for the penetration of the produced cuttings to enter into the hollow section. In order to trap the powder, the holes were made with a narrower section on the bottom such that the odds of exiting the hole once the powder enters the trap are minimized. Tests of the powder that is produced by USDC based mechanisms have shown that it does an outstanding job of generating powders for high quality X-ray diffraction spectra [18-19]. XRD patterns obtained from USDC generated powder are essentially indistinguishable from powders that were obtained using a laboratory Retsch mill. Also, the particle size distributions are quite comparable to the costly standard laboratory Retsch mills.

Fig. 6: The powdered-cuttings sampler in action drilling a limestone and accumulating cuttings inside the bit

IV. Various USDC configurations and designs

Operation in extreme environments

NASA strategic goals and science objectives are increasingly requiring future missions to be involved with robotic exploration of planets where the environment poses greater challenges to existing technologies. These extreme environments include very high temperatures such as found on Venus (460^{o}C) and very low temperatures as on Europa and Titan (-180^{o}C). In addition, potential mission may require sampling at very low gravity as is found on asteroids, and comets as well as at high pressure environments such as on Venus (90 bars). These challenges to the required technologies limit the in-situ possibilities that can be considered for these missions and are requiring new approaches using capabilities that currently are not available. While there is significant development of capabilities for low temperature applications the technologies for high temperature applications is still limited. For the low temperature range, the USDC was demonstrated to drill at temperatures as cold as -180^{o}C. Further, under an on-going PIDDP funded task, a USDC-based high temperature sampler is being developed for operation at the ambient temperatures of Venus. For this purpose, piezoelectric materials with a Curie temperature that is higher than 500^{o}C are being developed. Some of the potential candidates include; LiNbO3 and modifications of Bismuth Titanate and Bi(MgTi)O_3-PBTiO_3 and BST.

Ultrasonic/Sonic Gopher

The USDC mechanism was used to develop a "Gopher" that can acquire core samples using a bit diameter as large as 6.4 cm which was larger than the USDC actuator [16]. The device is shown schematically in Fig. 7, where a core is formed up to the length of the internal size of the bit and it is removed from the borehole. This process is repeated till the desired depth is reached. To demonstrate the capability of the Gopher it was tested on a glacier at Mt. Hood, OR and the lessons learned were implemented into the design and the enhanced Gopher was tested in Antarctica. The field test in Antarctica was conducted at Lake Vida and it provided an important opportunity to demonstrate the feasibility of this technology while determining the associated challenges and requirements to enhance its capability for future drilling objectives. The unit was successfully used to reach 1.76-m deep and it was a major milestone since it is significantly deeper than the length of the whole Gopher assembly.

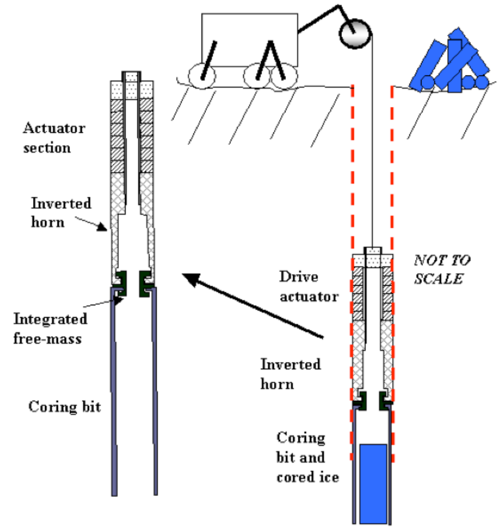

FIG. 7: Schematic view of the ultrasonic-gopher operating inside the borehole.

USDC-base rotary-hammer for rapid drilling

Lessons learned from the field test in Antarctica have shown that powdered cuttings removal is a significantly limiting factor in achieving rapid drilling to great depth. To effectively improve these two factors a rotation capability was introduced in the form of rotary-hammer. The hammering and rotation actuations were decoupled providing a drilling redundancy in case of failure of one of these two mechanisms. For the removal of the accumulating cuttings the bit was designed with flutes allowing the cuttings to be augered up the outer shaft of the core. The bit was designed with helical flutes that help the cuttings travel upward along the side of the bit to the surface of the penetrated medium. A graphic view of the bit is shown in Fig. 8. For the demonstration of the capability of the developed drill, a duty cycle of 20% and a preload of 5lb were used. The 14mm diameter bit was operated with ~100W continuous power and 6.5lb (~29N) weight on bit and it reached a depth of approximately 8.5-cm in a total continuous drilling time of 5 minutes. In a future study we plan to modify our U/S Gopher design using rotary-hammer capability to allow reaching as deep as 100-m in an autonomous operation..

Fig. 8: A graphic view of the USDC rotary-hammer bit.

Packed Soil Penetrator

Recently, a challenge was posed to penetrate packed soil to a depth of about 1 meter using 3.18 – 4.76mm diameter probes via low axial load. To insert a rod probe into this soil just by pushing requires a force of several hundreds pounds which could easily result in probe buckling. A novel Ultrasonic/

Sonic Impacting Penetrator (USIP) was developed and demonstrated to greatly reduce the required push force. In demonstration of the USIP capability it was shown that the required push force to penetrate highly packed soil down to about 1-meter was reduced from 200 lb to 7 lb. This effort involved modal and harmonic actuator analysis and system impact analysis. The modal analysis was used in the actuator design and the harmonic analysis to predict the actuator performance. The actuator design parameters were determined such that the mounting location coincides with actuator neutral plane. The impact analysis, which determines the interaction between the free-mass, the ultrasonic horn, and the bit, was used to derive an optimal weight of the free-mass.

Ultrasonic/Sonic Anchor

To support requirements for anchoring of legged and wheeled rovers, inflatable structures and landers the USDC offers significant advantages in its ability to operate via low axial load. Such a capability using a low mass device and relatively low power is needed to support platforms that would operate in low gravity environments and accessing steep slopes in rugged extraterrestrial terrains. A U/S Anchor was designed and fabricated using a modification of the USDC mechanism which drills at an angle with the normal to the surface. Operating the hammering action of the USDC in reverse allows its extraction from the medium onto which it was anchored and avoids possible jamming.

III. Lab-on-a-drill

The USDC was found to be able to sample, probe and sense and this integrated capability allowed for the design of a lab-on-a-drill system. Beside the inherent capability to core and sample powdered cuttings, the sensing is feasible since the bit does not rotate allowing for the easy of operating mounted sensors, while the hammering action provides a sounding mechanism. Two types of sensors were successfully demonstrated to date: thermocouple and fiberoptic. A thermocouple was used to measure the rate and maximum rise of temperature and these values were found to correlate to the hardness of the rock being drilled. Even though these thermal variables are dependent on the heat conductivity and capacity of the drilled object, one can assume with a reasonable accuracy that most rocks have thermal properties within a comparatively narrow range (with the exception of metal laden alloys ex magnetite). Compiling temperature rise rate and maxima as a function of time for a variety of drilled materials has demonstrated the feasibility of using a thermocouple-on-the-bit as a means of assessing the drilled medium hardness. Also, using an optical fiber provided a sensing capability where a fiber with approximately 160 μm diameter probe head was imbedded into 10-mm diameter coring bit with a 1-mm wall thickness. Reflection data in the wavelength range of 400-1200 nm were recorded. The use of fiberoptics with UV light in the range of 200-nm wavelength has the potential for identifying biological markers.

VII. Summary

The ultrasonic/sonic driller/corer (USDC) was developed to address requirements of future NASA missions. To allow effective design and construction of the various modifications of the USDC an analytical model was developed to predict its behavior towards the goal of optimizing its performance. Physical models were developed for each section of the device and their interactions. The developed models were integrated to allow investigation of the various interactions of the USDC and effective designs to support various applications. Various designs were developed and demonstrated including the Lab-on-a-Drill, Ultrasonic Gopher, soil penetrator and many others and various configurations of the horn and the bit were used to provide multi-functionality. The Lab-on-a-Drill is intended to take advantage of the probing capabilities of the USDC, the capability to sample cores and powdered cuttings as well as the fact that sensors can be easily mounted on the bit and allow real time data acquisition while drilling. The URAT was demonstrated to remove layers from rocks as hard as Basalt. The Ultrasonic Gopher operates in a cyclic mode of coring, uploading, core caching and downloading. This device was demonstrated to drill in ice in Antarctica reaching about 1.76-meter depth. The potential of the USDC is continuing to be investigated with the goal of producing the most benefits from its potential.

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